THE INOCULATION OF HYPO-EUTECTIC GRAY CAST IRON

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THE INOCULATION OF HYPOEUTECTIC GRAY CAST IRON

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ABSTRACT

Late additions of various grades of FeSi, CaSi, CaMnSi and other proprietary inoculants were made to cupola melted 4.1% carbon equivalent cast iron, to determine the effectiveness of various materials as inoculants, and to determine which elements contributed to the effectiveness of inoculants.

The tensile properties, transverse properties, hardness, and microstructures of inoculated irons were compared with the properties of uninoculated irons. In addition, a detailed study was made of the effect of inoculants on chill reduction in chill bars of various sizes.

It was concluded that calcium and aluminum are important ingredients in the best inoculants. High calcium 85% FeSi, CaSi, CaMnSi and Graphidox were particularly effective inoculants, which reduced chill and improved strength. It was also found that the behavior of the chill bar test varies as the size of the chill bar varies.

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The views expressed herein are the personal opinions of the author and are not necessarily the official views of the Department of Defense or a Military Department.

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INTRODUCTION

For many years foundrymen have utilized inoculation as a part of their standard practice. In the gray iron foundry, inoculation has been used for several purposes. These include: (a) reduction in chilling tendencies of soft irons to prevent hard edges in thin casting sections; (b) controlling chill to enable use of high strength, low carbon equivalent irons in thin sections; (c) overcoming minor variations in cupola practice and thereby producing a more uniform product; and (d) improving the mechanical properties of the cast irons.

Inoculation has been defined (1) as an addition for the purpose of altering or modifying the microstructure of the iron to improve the mechanical and physical properties to a degree not explainable on the basis of the change in composition. In this discussion the term "inoculation" will be specifically limited to late additions to the pouring ladles.

In order to study the inoculation of gray cast iron one must first consider the mode of solidification of this material. In brief, the solidification of hypoeutectic cast iron is a nucleation and growth process that occurs in stages. When a melt has cooled to the liquidus temperature solidification begins with the nucleation and subsequent growth of austenitic dendrites. As the temperature continues to decrease, the remaining liquid becomes enriched in carbon until the eutectic composition is attained at

the eutectic temperature. The melt continues to cool and when sufficiently undercooled the austenite-graphite eutectic transformation begins.

The transformation from liquid to solid is accomplished by nucleation at a number of discrete locations (nuclei) called eutectic cells (2) and proceeds by the growth of these cells along a spheroidal crystallization path. The eutectic cells continue to grow until they have impinged on one another and solidification is essentially complete.

The form and distribution of the graphite phase of the eutectic is determined by the composition, cooling rate, and degree of nucleation of the melt. The effects of the cooling rate and the degree of nucleation upon the graphite are best examined in relation to their effect on the degree of undercooling.

When gray iron solidification occurs with very little undercooling, only a relatively few nuclei are effective, and consequently there will be only a small number of eutectic cells growing in the melt. If the same iron solidifies with a large degree of undercooling, more nuclei in the melt will become effective, resulting in a larger number of eutectic cells growing. The increased undercooling also favors more rapid growth of the graphite flakes, whereas growth will tend to be slower when the undercooling is less. With large undercooling and rapid growth of graphite the flakes become finer, more branched and appear as Types D or E. The random, coarse, blunt flakes with few branches (Type A) result when

undercooling is minimized. Of course, if the melt undercools sufficiently, the stable austenite-graphite eutectic will be completely suppressed and solidification will occur as the metastable white iron eutectic of austenite and carbide. The degree of undercooling which actually occurs will be influenced by the rate at which the melt cools through the eutectic temperature range. If the melt is cooling very slowly, enough cells will be growing after only a small degree of undercooling that the heat liberated will be sufficient to arrest the temperature (and perhaps cause some recalescence). Solidification will be essentially completed with this minimal undercooling. If there is a higher cooling rate, the heat liberated by the few cells growing at a slight amount of undercooling will not be sufficient to arrest the temperature and further undercooling will occur until sufficient eutectic cells are nucleated and growing to arrest the temperature.

The effect of cooling rate on gray iron solidification can be summarized as follows: increased cooling rate increases undercooling, causes a larger number of nuclei and more eutectic cells. As undercooling increases, the growth rate increases which produces finer graphite flakes with more frequent branching.

Similarly, the effect of the degree of nucleation (graphitizing potential) of a melt can be related to undercooling. If a large number of stable nuclei are present in a melt, many eutectic cells will grow, and undercooling will be reduced. Since solidification of an effectively nucleated melt occurs with small undercooling,

growth of graphite will be relatively slow, and coarse blunt flakes will be produced. For a given composition, the best mechanical and physical properties are associated with the coarse, short flakes and Type A graphite. These conditions are promoted when solidification proceeds from a large number of eutectic cells with a minimum of undercooling. It follows that control of the nucleation condition of the melt by the addition of stable nuclei should exert a beneficial effect on the properties of the iron. This addition of stable nuclei is the contribution achieved by the practice of inoculation.

Inoculation has been practiced for many years. As early as 1922 a patented process using calcium silicon as an inoculant was developed. Almost all of the early investigators of inoculation were concerned with silicon bearing additions. Crosby and Herzig (3) in 1938 reported that the late addition of silicon was three times as effective as an equivalent amount in the charge. The silicon addition improved flake distribution and increased properties. The most common inoculant used in the early investigations was ferrosilicon. In 1943 Lownie (4) compared the effectiveness of ferrosilicon with silicon-manganese-zirconium. In his study the silicon-manganese-zirconium was a more effective inoculant than the ferrosilicon employed. It was noted that the greatest opportunity for improvement of properties occurs with high strength, low carbon equivalent irons, since these irons have the greatest tendency to solidify with Type D graphite. Burgess and Bishop (5)

in 1944, also reported the use of silicon-manganese-zirconium. They observed that inoculation extends the composition range of low chilling irons, and that the strength levels of high carbon irons were not materially improved by inoculation. In the early investigations, silicon was considered to be the important element in the inoculants and the presence of residual elements was usually unrecorded and was largely ignored. By the early 1940s, it was generally agreed that successful inoculation was accompanied by a change in graphite flake type from ASTM Type D and E to Type A, and that the degree of undercooling was reduced when inoculation was used. Since Type D and E graphite are most common in the high strength, low carbon equivalent irons, these irons were found to be improved the most dramatically by inoculation. It was, however, becoming apparent that more was involved in inoculation than silicon additions. Dierker (6) and others had successfully used graphite as an inoculant. In 1941, R. A. Clark, in a discussion of the work of Eash (7), noted that ferrosilicon was inefficient as an inoculant when it was low in aluminum content.

Finally in 1957, Womechel (8,9,10) and his associates considered the roll of the active metals in the inoculants. As a result of experiments conducted with low carbon equivalent cast irons, these workers concluded that calcium was a major contributor to inoculant effectiveness. Their work indicated that silicon was ineffective as an inoculant, aluminum reduced chill but did not promote Type A graphite and that ferrosilicon became more effective as its calcium and aluminum content increased. This last result very

seriously limits the usefulness of much previous work in which ferrosilicon was compared with other inoculants without consideration being given to the aluminum and calcium content of the ferrosilicon. Womechel also noted that calcium caused a slight reduction in the carbon content of the melt by formation of a low solubility calcium carbide.

Various theories have been proposed to account for the behavior of inoculants. R. A. Clark (1), McClure et al (10), Lownie (11), Morrogh (12), and others have discussed many of these theories. Most of the proposed theories have this in common: inoculation is explained as increased nucleation of a melt brought about by provision of stable effective nuclei. Some of the investigators consider these nuclei to be non-metallic inclusions of silicates, carbides, oxides, or sulfides. It is also suggested that the nuclei could be graphite particles or atomic irregularities on the interface between liquid and the austenite dendrites. While inoculants may modify the growth rate of graphite, it seems certain that the major effect of inoculation is the provision of additional stable nuclei. Fortunately we can study the effectiveness of these nuclei without knowing the exact nature of the nuclei.

Much of the work reported in the literature was performed on small laboratory heats. Usually the base metal was a low carbon equivalent cast iron prepared in an electric furnace. Since heats were limited in size, only one or two inoculants were compared with the base iron. Minor variations in composition and melting practice

can produce major changes in the microstructure and properties of gray cast iron, and therefore, the results of these previous studies may not be directly comparable to foundry grade cupola irons. The purpose of this investigation was to evaluate material presently used as inoculants for molten iron melted in a cupola. This study included an evaluation of various grades of ferrosilicon, other proprietary inoculants, combinations of ferrosilicon with other inoculants and a determination of the influence of the aluminum and calcium content of ferrosilicon on the effectiveness of inoculation. The use of molten iron from the cupola made possible large heats, so that in each experiment, at least six inoculated and one uninoculated iron could be compared and evaluated.

In order to provide a maximum of information upon which to base an evaluation (13,14) several types of castings were poured, and tensile properties, transverse properties, hardness, and section sensitivity were determined. The microstructures were examined for graphite flake size and distribution, matrix structure and eutectic cell size. Since reduction of chilling tendency is one of the major functions of inoculation, chill bars and wedges of several sizes were also poured.

MATERIALS AND PROCEDURE

Melting

For each of the five series of tests performed, gray iron was melted in an acid-lined, continuous tapping cupola at the Superior Foundry Company, Cleveland. A nominal 3.3% C, 2.0% Si gray iron was desired. The standard cupola charges were as follows (in pounds):

	Series				
Charge	A	B	C	D	E
Malleable Pig	700	700	700	700	700
Steel Plate Scrap	500	500	500	500	500
Sprue, gates, risers	765	765	765	762.5	765
Spiegel	20	20	20	20	20
Coke	240	240	240	240	240
50% FeSi briquettes	15	15	15	17.5	15

For each series, 1400 pounds of metal was poured from the cupola receiver into a holding ladle and moved to the pouring floor. For each sample within a series, 175 pounds of iron was placed in a pouring ladle. The 175 pound quantity was determined by filling the ladle to a predetermined mark. Inoculants were added to the stream as the metal entered the pouring ladle.

Additions

For Series A through D, the ferrosilicons, calcium-silicon, calcium-manganese-silicon, Graphidox, and SMZ were added in quantities calculated to produce a 0.3% Si addition to the 175 pounds

of molten metal in the ladle assuming 100% pick-up of the inoculant. Graphites were added on a basis of 2 pounds of graphite per 3 pounds of silicon as ferrosilicon. In Series E, the high Ca 85% FeSi was added as before, and the other inoculants were added on an equivalent cost basis. The result of this change in the basis of addition for Series E was a reduction in the amounts of the various inoculants used. In Series E the quantity of Graphidox was reduced to 55% of the amount added in Series C. Similar reductions for the other inoculants were: SMZ to 68%, CaSi to 51%, and CaMnSi to 46% of the amount added in other series.

The analyses of the inoculants used are as follows:

	Composition				
	Si	Ca	Al	Mn	Other
50% FeSi, standard	47.51	0.12	0.67		Bal. Fe
75% FeSi, standard	78.28	0.15	1.16		Bal. Fe
85% FeSi, standard	86.48	0.57	1.35		Bal. Fe
90% FeSi, standard	93.61	0.25	0.66		Bal. Fe
Silicon Metal	98.44	0.02	0.27		0.52 Fe
85% FeSi, Low Al	86.69	0.15	0.55		Bal. Fe
85% FeSi, Low Al, High Ca	89.06	0.65	0.44		Bal. Fe
85% FeSi, High Ca	85.61	1.60	1.64		Bal. Fe
CaSi	63.88	29.12	0.64		2.00 Fe
CaMnSi	55.22	13.88	0.67	18.60	9.30 Fe
SMZ (nominal)	62			6	6 Zr; Bal. Fe
Graphidox (nominal)	50	6			10 Ti; Bal. Fe

The inoculants were received in 25 or 50 pound containers. Random samples were prepared by repeated subdivision of the entire quantity in a sample splitter, to insure that the sample was representative of the entire lot.

Molding, Pouring and Shake Out

From each 175 pound ladle, the following castings were poured after inoculation:

1) one step casting with steps of 1/4", 1/2", 1", 1 1/2" and 2" thickness as shown in Figure 1. The overall casting dimensions were 12 1/4" x 6"

2) one cluster of four bars 1.2" in diameter x 21" long (ASTM size B) cast vertically (ASTM-A438-60T)

3a) one size W4 chill wedge (Series A only) (ASTM-A367-60)

3b) one size W2 chill wedge (Series B through E) (ASTM-A367-60)

4a) two size 5C chill bars cast against a plate (all series) (ASTM-A367-60) (thick bar, approximately 5/8 x 1-1/2 x 5 1/2 inches)

4b) two size 2C chill bars cast against a plate (Series B through E) (ASTM-A367-60) (thin bar, approximately 1/4 x 1-1/2 x 3-1/2 inches)

The step castings and arbitration bars were cast in green sand molds prepared in the regular molding lines of the cooperating foundry. The chills were cast in oil-bonded sand core molds. After inoculation the castings were poured at about 2500°F, allowed to cool in the molds overnight and shaken out cold.

Testing

The bottom face of each step of the step casting was cleaned by a light milling cut and four Brinell hardness readings were obtained from each step face.

Each 21" arbitration bar (ASTM size B) was placed on 18"

supports and broken under a centrally located transverse load (ASTM-A438-60T). Loads and deflections were recorded. The modulus of rupture and transverse modulus of elasticity were determined in accordance with ASTM recommendations. Metallographic and tension specimens were prepared from the broken transverse test bars. All specimens were taken from the lower half of the bars as cast vertically in the molds. A one inch thick disc was removed from the fractured end of the bar for metallographic examination. After the fractured surface was removed, the Brinell hardness was measured on one face and the opposite face polished. This surface was examined in the unetched condition to evaluate the graphite flake size and distribution. It was then etched in 6% picral and examined. The percent of ferrite in the otherwise pearlitic matrix was determined. This face was then repolished and etched with Stead's Reagent to determine the eutectic cell count. The tension test specimen was prepared from the section of the broken transverse bar adjacent to the disc and approximately 4" of the bottom of the casting was discarded. The tension test specimen was an ASTM (E8-57T) number 2 specimen with .750 ± .015 inch diameter, threaded ends (1-1/8 x 7 - 2A threads), and 1 inch gage length. Each specimen was mounted in a testing machine with self-aligning grips and a separable extensometer (Linear Variable Differential Transformer). The load was obtained from foil type strain gages arranged in a 4-arm external bridge. The extensometer and strain gages are illustrated in Figure 2. Impulses based on the load and

extension values were supplied to an X-Y recorder as shown in Figure 3. The loads were calibrated with the readings on the testing machine dial. The extensometer was calibrated in a drum micrometer (Figure 4).

Chill specimens were broken cold and both total and clear chill were recorded. Specimens and measurements were in accordance with ASTM-A367-60. At least one sample from each series was analyzed for C, Si, S, P, Cu, Mn, Mo, Ni and Cr. Each sample in all series was examined for Si. In each series, at least three samples were analyzed for C, including the first and last samples poured. Analyses were also taken to determine the residual amount of other elements, except calcium, added by inoculation.

RESULTS AND DISCUSSION

The purpose of inoculation of gray iron is to reduce the chilling tendency and increase the mechanical properties. In general, the mechanical properties of gray iron depend upon the size of the eutectic cells, the amount, size and distribution of graphite flakes, and upon the matrix. These, and the chilling tendencies depend upon the composition, cooling rate, and state of nucleation of the iron. In this investigation, comparisons were made under conditions of similar cooling rates although the cooling rate did vary from the outside to center of the bars cast. The mechanical properties, including the tensile and transverse strength, ductility, modulus and hardness on both 1.2" diameter test bars and step bar castings, were investigated for various inoculants. The depth of chill, graphitic and matrix microstructures were also determined for each state of inoculation.

Chemical Composition

Since both the carbon equivalence and alloy content of a gray iron influence the mechanical properties, chilling tendencies and microstructure, it was necessary to observe the variation in composition.

In addition, an examination of the chemical analysis provides an indication of the inoculant recovery. The analyses of all inoculated specimens in each series are shown in Table I.

With the exception of Series B, the compositions of the five series are very similar. The carbon equivalence* is very similar in Series A, C, D and E. The average carbon equivalence of the uninoculated or control irons in Series A, D and E is 4.01% with a maximum variation of .04% and after inoculation the average carbon equivalence of Series A, C, D and E is 4.15% with a maximum variation of this average of only .03%. The carbon equivalence of Series B, however, is somewhat lower; the carbon equivalence of the uninoculated iron is 3.89% and the average carbon equivalence of the inoculated irons in this group is 3.94%. In addition, the alloy content, including chromium, molybdenum, nickel and copper, of Series B is somewhat higher than the other groups. The difference in molybdenum and nickel is particularly marked with a .18% Mo, .25% Ni in Series B compared to an average of .07% Mo and .05% Ni in the other four series. The manganese, sulphur, and phosphorus contents (.71% Mn, .093% S and .054% P) are very similar in all series.

The recovery of the inoculants was generally very high. Over 85% of the silicon content of most of the additions was picked up by the molten iron. The exceptions to this behavior were only 50% recovery of the silicon content of the CaSi and CaMnSi in Series B, and the 50% grade FeSi in Series C. The recovery of the graphite was erratic because of difficulties of addition, with considerable loss of fines and floating of the graphite on the surface of the

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* All parameters and quantities subject to arbitrary definition are defined in an Appendix, following the text.

liquid metal. In some cases only a very slight recovery of carbon was obtained.

Tensile Properties

The tensile properties data provides an indication of the effect of various inoculants on these important properties and the influence of carbon equivalence on the effect of inoculation. The tensile strength, yield strength at .2% offset, modulus of elasticity and yield-tensile strength ratio are shown in Table II. The tensile strength is plotted in a bar graph in Figure 5. The yield strength values are not usually reported for gray iron because of difficulty in obtaining a reliable stress-strain curve. However, with the special equipment reported in the procedure, these measurements were feasible. The yield strength generally follows the tensile strength. However, no direct correlation between the yield-tensile ratio and tensile strength or modulus of elasticity is apparent.

The overall effect of inoculation on the tensile strength varies widely from series to series. Inoculation decreased the strength of Series A; sharply increased the strength of Series B and either slightly increased or slightly decreased the strength of Series D and E. No comparison with the uninoculated iron is possible in Series C since no control specimen was included. It is pointed out that inoculation does increase the carbon equivalence in these experiments. The average carbon equivalence was increased .14% in Series A, D and E by inoculation and only .05% in Series B. This increase in carbon equivalence exerts a depressing effect on the strength. A more

accurate measurement of the effect of inoculation on strength would be to compare similar compositions where the higher carbon equivalence of the uninoculated iron exists in the metal that flows from the cupola. Under these conditions equivalent compositions can be compared. The only significant difference is whether the added silicon is placed in the cupola charge or added to the ladle during inoculation. In addition, the tensile strength of the higher carbon equivalent irons such as the types investigated in this work is known to be only slightly influenced by inoculation compared to the lower carbon equivalent metals. Series B was the lowest carbon equivalent and highest alloy iron and it is therefore to be expected that the greatest increase in strength from inoculation is obtained with this series (15). Series D and E are influenced in a fairly conventional manner by inoculants. The general decrease in strength obtained by inoculation in Series A has been observed in other work (16), requires a special explanation and will be discussed in other sections of this thesis.

The effect of the individual inoculants on tensile strength is shown by a comparison of the relative strength within each series. The different general effect of inoculants on strength within each series permits a comparison of the various inoculants in irons of different types. The strength of the sample inoculated with the standard 85% grade of FeSi was slightly higher than the other standard grades in Series A; the silicon metal and 75% grade of FeSi exhibited the lowest strength, and the 50% and 90% grades

were intermediate in behavior. Series B was conducted to compare the inoculation effect of various grades of 85% FeSi, CaSi and CaMnSi. The greatest increase in strength was obtained by inoculation with high calcium FeSi and CaSi; CaMnSi and the standard 85% FeSi were intermediate in behavior; inoculation with the low aluminum grades of FeSi resulted in the lowest strength. This indicates the necessity for the presence of aluminum and calcium in the inoculant to obtain effective action (16). The highest tensile strength in Series C was obtained by inoculation with Graphidox. The 85% standard FeSi, graphites and 50% FeSi were intermediate in behavior and the SMZ and the combination of 85% standard FeSi and flake graphite yielded the lowest strength. This series again indicates the effectiveness of the higher calcium (and possibly titanium) in the Graphidox. The 85% and 50% standard grades of FeSi contain sufficient calcium and aluminum to be fairly effective in improving strength. It is also apparent that graphite additions can be reasonably effective inoculants, although these additions are not as effective with FeSi as alone. This is somewhat at variance with previous work (16). The SMZ inoculant without appreciable aluminum or calcium is not an effective inoculant.

The comparison of the effect of inoculants on the tensile strength observed in the first three series is also shown on Series D and E. In Series D, the iron inoculated with high calcium FeSi had a slightly higher tensile strength than the base iron, whereas the 50%, 75% and 85% standard FeSi cause a slight reduction in

strength. The silicon and 90% FeSi inoculated irons had the lowest strengths in this series. This again indicates that aluminum and calcium are good inoculants and the additions containing more of these metals are more effective. The higher calcium-containing inoculants produce the highest strength in Series E. CaMnSi, CaSi and Graphidox increase the strength of the base composition. The high calcium grade of 85% FeSi added alone and with Mexican graphite results in a tensile strength close to the uninoculated iron. Addition of SMZ, however, decreases strength appreciably.

The modulus of elasticity, as listed in Table II shows some evidence of being influenced by inoculants in a similar manner as the strength. However, sufficient variations occur that no general statement can be made. Some of the more outstanding variations are the high modulus of the 75% standard grade of FeSi in Series A, and the low modulus of elasticity observed with CaMnSi additions to Series B and E and low modulus of additions of 85% FeSi plus graphite in Series C and E. Some difficulty was experienced with bending, and with plotting the stress-strain curve. For this reason the modulus of elasticity and yield strengths are not considered to have the same high accuracy obtained with the tensile strength.

Transverse Properties

The transverse test results for the various irons are similar to the tensile strength results throughout the five series. The transverse strength, represented as modulus of rupture, transverse

modulus of elasticity and total deflection are listed in Table II. The modulus of rupture and deflection are plotted with the tensile strength in Figure 5. An examination of the latter figure demonstrates the similarity between the tensile strength and modulus of rupture. The difference between the effect of the various inoculants in each series is more marked in the tensile strength because of the nature of the tests but the direction of the effect on strength is generally very similar. In the transverse test, the bottom of the bar under the applied load is under tensile stress while the top of the bar is loaded in compression. Since the modulus of elasticity and strength are higher in compression and tension, any differences in strength are reduced in magnitude compared to the uniform uniaxial tension in the tensile test.

The deflection is not as sharp a criterion for measuring the relative effect of the various inoculants. The data provides an indication that the stronger irons deform somewhat more than the lower strength irons. This type of behavior has been previously observed by many other investigators. The nature of the test tends to reduce the magnitude of these differences and provide some scatter in the results.

The calculated transverse modulus of elasticity data also indicates that a somewhat higher modulus is to be expected with the stronger irons. The effect is somewhat masked, however, by the test and material variations that influence the breaking load and deflection. Since the calculation of modulus of rupture is based upon the breaking load, and the transverse modulus of elasticity is

based upon the breaking load and the deflection, this variation is to be expected.

Hardness Readings

Hardness readings were made on the cross section of the 1.2" transverse bar for comparison with the tensile properties and on the steps of the step casting to determine the influence of inoculation on the section sensitivity of the various irons. The data from the 1.2" test bars are plotted in a bar graph in Figure 6. The hardness at the center and near the outside are both shown when a difference exists. The variation in hardness at different thicknesses in the steps is illustrated in Figures 7 to 11 for Series A to E respectively.

The influence of inoculation on the test bar hardness is similar in some respects to its effect on the tensile strength, although this correlation is influenced by structure. Since the structure does change somewhat depending on the effectiveness of the inoculation, these variations can be expected.

In Series A, the hardness of all inoculated irons was at least 19 BHN lower than the base iron. The variation is generally similar to that in tensile strength. In Series B, CaMnSi reduced hardness but increased strength, an indication of a desirable inoculant. Only the 85% FeSi in the standard, low aluminum and high calcium grades increased Brinell hardness compared to the base iron. The iron inoculated with SMZ in Series C had the lowest hardness and

strength in that series. The standard 50% FeSi, and the combination of 85% FeSi and flake graphite also reduced hardness. In Series D, the hardness and tensile strength of irons inoculated with standard 75% and 85% FeSi remained at the same level as the base iron. All other inoculants reduced hardness, with the largest reduction occurring with 90% standard FeSi and the high calcium 85% FeSi. This latter inoculated iron, however, had the highest strength in this series. SMZ again produced an iron of substantially lowered hardness and strength in Series E. The CaMnSi also reduced the hardness of the base iron sharply but exhibited a substantial increase in strength over the base iron and was the highest strength iron in this series.

The hardness of each step in the step bar castings was reduced by the addition of all inoculants compared to the uninoculated or control specimen. The spread in hardness from the 1/4" to 2" thick steps of each iron varied from 20 to 55 BHN. This variation was fairly uniform for the uninoculated irons (28-44 BHN) but varied widely for the various inoculants.

In Series A, the difference in hardness from the 2 inch section to the 1/4 inch section was 44 BHN in the base iron. This difference was reduced to 25 BHN by the 90% FeSi and approximately 30 BHN by the other standard FeSi's and by silicon metal. All inoculants reduced the hardness about the same amount. The section sensitivity was not as greatly influenced by inoculation in Series B and D, in which CaSi, CaMnSi and various grades of FeSi were

compared. In Series C the graphites and some proprietary inoculants were compared with standard grade 85% FeSi. The standard 85% FeSi produced the lowest level of hardness. The section sensitivities were comparable, except in the case of the iron inoculated with Graphidox. This iron had an increase in hardness of 51 BHN in going from the 2 inch to the 1/4 inch section.

The base iron used in Series E was less sensitive to section size than the other irons used. The difference in hardness in the 2 inch and 1/4 inch sections was only 27 BHN. This difference was slightly reduced by inoculation with the combination of high calcium 85% FeSi and Mexican graphite. Both high calcium 85% FeSi and the SMZ showed a large difference in hardness in going from the 2 inch to the 1/4 inch section. This was due to the very low hardness (130,135 BHN) in the 2 inch section, rather than any unusual increase in hardness in the thin sections.

Chill Tests

One of the major purposes of inoculation, especially in irons of high carbon equivalence, is chill reduction. The effectiveness of the inoculants in reducing chill is illustrated in Figure 12. All inoculants in all series produced some chill reduction. In Series A, only the thicker (5/8" thick) chill bar was used, and standard grades of FeSi were compared. The greatest reduction in chill occurred with the 50% and the 85% FeSi. The 90% FeSi and silicon metal were least effective in this respect and the 75% FeSi

was intermediate in behavior.

In Series B through E a thin (1/4") chill bar was used in addition to the thick bar used in Series A. This thinner chill proved to be an excellent measure of chill behavior. The ASTM W2 wedge chill was also used, but was not very sensitive for evaluating chill behavior. The same inoculants were compared again in Series D, along with a high calcium, 85% FeSi. The silicon metal was again shown to be ineffective in chill reduction in both thick and thin sections. This latter addition also reduced the tensile strength of the uninoculated iron because of its effect on carbon equivalence. The standard 50%, 75%, and 85% FeSi showed the lowest chill in the thick bar, and a slight reduction in tensile strength. The high calcium 85% FeSi increased tensile strength slightly and provided the best chill reduction in the thin bar. The standard 90% FeSi also produced very good chill reduction, but in this case the tensile strength was reduced.

In Series B, all inoculants increased strength and reduced chill. Those inoculants which produced the highest strengths, in general showed the lower chills. The lowest chill in the series occurred with high calcium, 85% FeSi, which produced a relatively high strength iron. The iron inoculated with CaSi had slightly higher strength than the iron inoculated with high calcium, 85% FeSi, but the chill depth was slightly higher. The iron inoculated with CaMnSi had a chill depth slightly less than the CaSi inoculated iron and a slightly lower strength. This latter

inoculant was greatly superior to the low aluminum ferrosilicon as an inoculant. The relatively poor performance in chill reduction of the low aluminum grades of ferrosilicon is further evidence of the importance of this element in effective inoculation.

The standard 50% and 85% FeSi, Graphidox, SMZ and Mexican graphites in Series C produced low chill in the thick bar. Flake graphite and the combination of flake graphite and standard 85% FeSi produced a slightly deeper chill than the other additions in this bar. In the thin chill bar, however, the SMZ and the combination inoculant showed a deep chill, the chill remained low with flake graphite and with 50% FeSi additions but sharply increased with Mexican graphite inoculation. All inoculants provided substantial chill reduction in the thick bars of Series E. Once again, however, the behavior changed in the thin bars. In this case SMZ and Graphidox were ineffective in the thin sections but the chill reduction with 85%, high calcium FeSi plus Mexican graphite, CaSi and CaMnSi remained excellent. Since the two latter inoculants improved the strength and the FeSi plus graphite combination did not, these are the preferred additions. Since the chill behavior of irons varies not only with changes in inoculants, but also with changes in the size of chill bars, some discussion of the behavior of the chill bar test is warranted. A chill block test involves the pouring of molten iron into a mold of an oil-bonded sand core placed on a large steel block (chill). The chill bar is, therefore, subject to slow cooling through the sand walls and rapid cooling through the chill (12). The effect

of the chill is to cause a very rapid but progressively decreasing cooling rate to commence at the chill and advance inward. At any point in the bar removed from the chill, a definite time must pass before the rapid cooling effect can reach it. Since a very rapid cooling rate through the eutectic range causes white iron solidification, and a slow cooling through the eutectic range results in gray iron solidification, some critical cooling rate exists that separates white from gray solidification.

In the chill bar, the transition from white to gray iron marks the depth at which the critical cooling rate was reached. In these experiments, the pouring temperature was held constant, so the cooling rate conditions in a given type and size of chill casting were the same. A decrease in chill depth under these conditions can safely be interpreted as an increase in nucleation of the melt. That is, with an increase in nucleation of the melt, an increased cooling rate will be required in order to produce white iron. In experiments B through E, two thicknesses of chill bars were used. The solidification time for the thicker bar at 1 1/2 inches from the chill face was calculated to be approximately 3.5 times as great as the solidification time for the thinner bar. This means that the cooling rate at any particular distance from the chill in the thin casting was greater than the cooling rate in the thick casting at the same distance from the chill. The result was that the critical cooling rate occurred at a greater distance from the chill in the thin casting, and this casting could therefore, be

expected to show somewhat deeper chill than the thick casting. This was the chill behavior found most frequently in these experiments, and is the normal behavior expected with an iron of fairly high graphitizing potential.

This behavior is not, however, the only possibility. If a cast iron has a very low state of nucleation, its depth of chill in the chill bar test will be determined by an interplay between the rapid cooling rate progressing inward from the chill face and the slow cooling rate progressing inward from the sand core (12). In this case, the eutectic transformation may be caused by the slow cooling rate to produce gray iron or by the rapid cooling rate and solidify as white iron. Under these latter conditions, a thin chill bar can be slow cooled through the eutectic range before the onset of the rapid cooling rate at a point closer to the chill than will be the case with the thick chill bar. Thus, thick chill bars will actually show greater chill depths than thin bars, if the iron has a very low graphitizing potential. It is not believed that this latter behavior occurred in this investigation. The explanation is included for the sake of completeness.

While the foregoing may assist in explaining the behavior of a particular iron with a given inoculant in chill bars of various thicknesses, many other factors also influence the behavior of chills. Figures 13A and 13B illustrate the depth of chill obtained in Series D and E respectively with two inoculants as a function of the chill bar thickness. It is seen that the irons treated with 50% standard FeSi and SMZ showed lower chill than the irons treated with high calcium

85% FeSi and CaSi respectively in the thicker chill bar, whereas the reverse was true in both cases in the thin bar. This behaviour can be explained by considering the effectiveness of inoculation under the varying conditions which appear in the chill bars. Figure 14 is a schematic representation of this situation involving two independent variables. The effectiveness of inoculation or number of active nuclei is plotted on the abscissa. Several equivalent functions are shown on the ordinate. As the thickness of the chill bar increases, the time to solidify (calculated for a distance 1 1/2" from chill face) increases. The cooling rate at a specified location will, therefore, increase as the chill bars become thinner. For a given degree of inoculation, as the cooling rate at a specified location increases, solidification will change from gray to mottled to white. On the other hand, for a given cooling rate, solidification changes from white to mottled to gray with an increase in effective inoculation. Solidification behavior, then, is a function of both cooling rate and effectiveness of inoculation and the effectiveness of a particular inoculant must be measured as a function of cooling rate in order to evaluate it properly as shown schematically in Figure 15. In Figure 15 it is seen that the hypothetical inoculant "A" which is relatively more effective (more active nuclei) than "B" at slow cooling rates, increases in effectiveness only slightly as the cooling rate increases. Inoculant "B", however, increases in effectiveness rapidly as the cooling rate increases and is more effective than "A" at high cooling rates. For a given thickness of

chill bar, (fixed cooling rate conditions at the specified location) the more effective of two inoculants causes lower chill since an increase in inoculant effectiveness decreases chill depth. Thus, for the two hypothetical inoculants "A" and "B" above, Figures 15A and B are directly comparable. This proposed behavior explains the experimental result previously noted in Figure 13.

To state this in slightly different terms, within the range of eutectic transformation, the degree of nucleation provided by a particular inoculant is a function of the amount of undercooling. With some inoculants, almost all of the increased nucleation may be made available with a moderate amount of undercooling, and very little additional nucleation made available with greater undercooling. Other inoculants may provide some nucleation at a small degree of undercooling and continue to provide an increasing amount of nucleation as undercooling increases.

This result has important implications for the foundryman. The chill bar test is used as an aid to the control of the cupola operation and for this purpose a particular size of chill bar may provide an adequate measure of changes in the iron. If, however, the chill test is to be used to measure the effectiveness of inoculants, it must be recognized that the outcome of the test will depend upon the size of chill bar used. In the foundry, the size of chill bar must be related to the section size of casting poured, to insure similar cooling conditions. If this effect is not considered, the inoculant or inoculating practice selected as best on the basis of a chill test, may not provide the best inoculation for the castings poured.

Microstructure

The properties of gray iron are functions of the graphitic flake size and distribution, matrix structure, and the eutectic cell size. In order to evaluate completely the effectiveness of inoculants it was necessary to consider their influence on these microstructural factors. In this investigation, the irons were slowly cooled and had a pearlite matrix, occasionally interrupted by free ferrite regions. These ferrite regions were contiguous with graphite flakes in the usual manner. The effect of inoculants upon eutectic cell size is illustrated in Figure 16. Bar graphs in this figure show the number of eutectic cells per square inch of specimen. The values represent an average cell size of the total cross section of the 1.2" bar used since the areas near the center generally have larger cells than near the surface. The relative percentage of ferritic matrix areas are also shown in a separate bar graph in Figure 16. The graphitic flake size measured in the 1.2 inch diameter bar section is shown in Table III. These measurements are also average values considering center and surface locations.

Inoculation always decreased the size of the eutectic cells, although the amount the cell size is reduced varies considerably with different additions. Inoculation also transformed some or all of the Type D graphite in the uninoculated irons to Type A. The only appreciable quantities of Type B graphite were found in Series A and are reported in Table III. The base iron in Series A had large eutectic cells, and its graphite distribution was approximately 80% Type D. Inoculation with silicon metal in this series

produced only slight increases in the eutectic cell count (number of cells per square inch). The standard ferrosilicons were somewhat better in this respect, with the 85% FeSi producing the highest cell count in the series, and the 90% FeSi iron having the lowest cell count of the FeSi inoculated irons. Each of these inoculated irons essentially eliminated Type D graphite, converting it to Type A with the 50%, 75%, and 85% additions and to Type A and B when silicon metal and 90% FeSi were added. The flake size was elongated by 50%, 75%, and 85% FeSi inoculation.

Each of the inoculants in Series A caused an appreciable increase in the amount of ferrite in the matrix. The amount of ferrite in the irons inoculated with 50% and 85% FeSi was slightly smaller and those irons inoculated with 75% FeSi, 90% FeSi, and silicon metal contained somewhat higher amounts of ferrite than average.

In Series B, the low aluminum grades of FeSi produced only very slight increases in eutectic cell count. The best inoculants in the series, from the standpoint of high cell count, were CaSi, CaMnSi, and high calcium 85% FeSi, in that order. In this series, the base iron had only 5% of its graphite in the Type D distribution, and this was reduced in all cases. The amount of ferrite in the matrix was low in the base iron and remained at about the same low level in all of the inoculated irons.

The highest cell counts in Series C were produced by the inoculation with Graphidox, standard 50% FeSi, and with flake graphite. The standard 85% FeSi and the combination of 85% FeSi with flake graphite contained fewer cells indicating less effective inoculation. About 5% of the graphite was Type D in the sample

inoculated with flake graphite. All the other irons had less of the Type D distribution. In this series, the iron inoculated with SMZ had a high ferrite content, when compared to the other irons in the series. The amount of ferrite in the irons inoculated with the other additions and the uninoculated iron were similar.

In Series D, inoculation again decreased eutectic cell size in all cases. Once again the standard 90% FeSi and the silicon metal were the least effective in reducing cell size and the 50% FeSi only slightly better. The high calcium 85% FeSi was superior to all other inoculants in the series in cell size reduction. The 85% FeSi was the best of the standard grades, though less effective than the high calcium grade in cell size reduction. All inoculants, except 75% FeSi decreased the amount of Type D graphite. Inoculation produced an increase in graphite flake size in this series. The effect was most noticeable with standard 50% FeSi and high calcium 85% FeSi. The irons inoculated with standard 75% and 85% FeSi contained only a slightly larger amount of ferrite in the matrix than the base iron, but additions of the standard 90% FeSi, silicon metal, and high calcium, 85% FeSi produced considerably more ferrite than the base iron.

In Series E, all irons had a substantial increase in eutectic cell count produced by all types of inoculation. The highest cell counts were obtained with CaSi and Graphidox. The Type D graphite in the base iron was almost entirely eliminated by each of the inoculants compared in this series and the size of the graphite

flakes was increased. The amount of ferrite in the matrix was relatively unaffected by inoculation except for a substantial increase when SMZ was added and some increase from 85% high calcium FeSi addition.

General Evaluation of Inoculation Effect

The general effect of inoculants on gray iron castings is obtained by a comparison of the mechanical properties and microstructure. The eutectic cell size exerts a considerable influence on the properties, particularly the tensile strength, because it affects both the graphitic structure and the matrix to a lesser extent. In this investigation, as inoculation increased the eutectic cell counts, the strength of the irons increased, as long as the inoculation did not additionally produce an increase in the amount of free ferrite in the matrix. In the case of all inoculants in Series A and the SMZ inoculation in Series C and E, higher ferrite contents resulted from these additions and the strength decreased. In most other cases the increase in eutectic cell count did produce the expected increase in strength. Thus, in Series B, in which the ferrite content remained low, inoculation increased both tensile strength and eutectic cell count. The higher strengths occurred with the irons of highest cell count. The lack of a control iron makes analysis of Series C somewhat uncertain, but some observations can be made. In this series, flake graphite produced a slightly higher eutectic cell count

than Mexican graphite, but a higher strength level occurred with the Mexican graphite. Since the free ferrite content in each was the same, the slightly lower strength of the iron inoculated with flake graphite must be attributed to the small additional Type D graphite and slightly less desirable graphite distribution found with the flake graphite inoculation. In Series D and E the strengths of the iron increased as eutectic cell count increased except for SMZ and 90% FeSi when a large ferrite content in the matrix reduced strength.

Successful inoculation usually increases tensile strength, and decreases the hardness slightly. When inoculation produced decreased strength due to ferrite, however, the hardness was sharply reduced. If the hardness of the irons in each series is compared with the amount of ferrite in the matrix, a very close correlation is observed. In Series C and E the SMZ produced irons of a much lower hardness than the other irons within the series. In Series D standard 90% FeSi, silicon metal, and high calcium 85% FeSi produced irons of a reduced hardness. In Series E, in addition to the SMZ, high calcium 85% FeSi produced lowered hardness. In each of these cases the reduction in hardness was accompanied by a proportionate increase in the amount of ferrite in the matrix. Inoculation nearly always reduced hardness, but this reduction was large only in the cases where ferrite was the cause. This behavior is in agreement with the work of many other investigators and provides further evidence that hardness of gray iron is primarily determined by the matrix and does not depend directly upon the

eutectic cell size or graphite distribution. It does, of course, depend on the amount of graphite, but this is relatively constant because of the similarity of compositions.

The deflections observed in the transverse bend test were generally highest when eutectic cell counts were highest. The deflections were not decreased by the presence of free ferrite, however. In fact, irons of low cell count had high deflection if relatively large amounts of ferrite were present. In Series C the deflection increased as the eutectic cell count increased, except in the case of inoculation with the combination of standard 85% FeSi and flake graphite. This iron had one of the largest cell sizes of the series but also the largest deflection. A similar situation occurred with 90% FeSi inoculation in Series D and SMZ inoculation in Series E.

The graphite flake size and distribution gives an indication of gray iron quality, but is a much less precise parameter than is eutectic cell size. The best properties occurred in Series B, in which the irons had almost entirely Type A, size 4 and 5 graphite. As previously noted, the effect of graphite flake size and distribution in Series A was completely masked by the effect of the ferrite in the matrix. The Type D distribution was found only with irons of generally lower properties. The large quantities of unusually large graphite flakes in Series D and E were associated with irons of only intermediate strength levels. Within a series, it is not possible to select among the inoculants, based only upon

the size, shape and distribution of graphite flakes. Considering the mode of solidification of gray iron, it is seen that the eutectic cell size is related to the graphite distribution. Whereas it is possible to measure cell size directly, it is difficult to obtain an adequate quantitative description of the graphite flake. In this investigation, the size, taken with the ASTM classification of distribution was inadequate for the purpose of differentiating among the inoculants.

Microstructure can also be related to chill tendency. In general, inoculation that produced the largest decrease in cell size, also produced the largest chill reduction. In Series A, where only the thick chill was used, the 90% FeSi and silicon which were the poorest in reducing cell size were also seen to be poorest in chill reduction. In Series B through E, the thin chill bar was a more sensitive indicator of the correlation between cell size and chill reduction. The low aluminum ferrosilicons of Series B, which were reported to be ineffective as chill reducers, also had the largest cell size of the inoculated irons in that series. Series C and D also behaved conventionally with the smallest cells occurring in the irons of lowest chill. In Series E, cell sizes of the inoculated irons were smaller and the chill lower than the base iron, but among the particular inoculants, there was not complete correlation between cell size and chill reduction. The SMZ and Graphidox inoculated irons in this series have relatively high cell counts, but the highest chill of the inoculated irons in the series.

CONCLUSIONS

1. The high calcium 85% FeSi, CaSi, CaMnSi and Graphidox are effective inoculants in a 4.1% carbon equivalent, cupola melted iron as measured by chill reduction and improved tensile strength. The standard grade 50% FeSi is a good chill reducer, but does not improve the tensile strength. Silicon metal, 90% FeSi, and SMZ are relatively ineffective inoculants. The low aluminum grades of 85% FeSi, are only fair inoculants, even when they have high Ca content. The flake and Mexican graphites are fair inoculants and are slightly better when added without rather than with FeSi. The effectiveness of the best inoculants is a function of calcium and aluminum content.

2. Successful inoculation is accompanied by an increase in the number of eutectic cells. This supports the theory that inoculation operates by providing active nuclei from which eutectic cells can grow. All good inoculants reduce the chill considerably in all cases.

3. The good inoculants will improve the strength of gray iron unless some ferrite is produced in the matrix by inoculation. In this latter case, the hardness is sharply decreased at all section sizes. When the strength is improved by inoculation, the hardness is slightly to moderately reduced simultaneously. This fact provides further evidence of the lack of correlation between hardness and strength in gray iron.

4. Effective inoculation changes the graphite distribution from Type D (if any exists) to Type A. Contrary to previous thought this change may not be accompanied by an increase in tensile strength. In such cases inoculation has increased the percentage of ferrite in the matrix.

5. If the effectiveness of inoculation is to be measured by the use of chill bar tests, then the chill bar must be of proper size to provide the same cooling rate conditions as found in the castings.

6. Inoculation changes not only the eutectic cell size and graphitic distribution, but also the stability of the pearlite in the matrix.

APPENDIX

Many of the terms or calculated quantities relating to gray iron are subject to arbitrary definitions. The following are the definitions of such terms as used in this paper.

Carbon Equivalent: $C.E. = \%C + \frac{\%Si}{3}$

Tensile Properties:

Tensile Strength: $T.S. = \frac{\text{max. load}}{\text{orig cross-sectional area}}$ (Psi)

Yield Strength: yield strength at .2% offset.

Modulus of Elasticity: Secant Modulus, calculated at 1/4 of the breaking load.

Transverse Properties

Modulus of Rupture: $M_r = \frac{2.55\ SL}{D^3}$ (psi)

S = actual breaking load (lbs)

L = dist. between supports (inches).

D = actual dia. of bar (inches)

Transverse Modulus of Elasticity:

$E_a = 0.424\ \frac{SL^3}{YD^4}$ (psi)

Y = defl. of bar when S is applied (inches)

Reported Deflection = $\frac{\text{actual deflection}}{I}$

where I = correction for size of bar, taken from ASTM A438-60T

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TABLE I - Chemical Analyses of Various Heats, Before and After Inoculation

	Inoculants	C ± .05	Si ± .10	S	P	Cu	Mo	Mn	Ni	Cr	Other
Series A	Uninoculated	3.25	1.91	.096	.055	.09	.07	.71	.07	0.11	
	50% FeSi,Std.		2.45								
	75% FeSi,Std.	3.27	2.47								
	85% FeSi,Std.	3.40	2.48								
	90% FeSi,Std.		2.42								
	Si Metal	3.38	2.42								
Series B	Uninoculated	3.19	2.10	.090	.042	.12	.18	.67	.25	0.20	
	85% FeSi,Std.		2.35								
	85% FeSi,Low Al		2.33								
	85% FeSi,Hi Ca	3.13	2.31								
	85% FeSi,Low Al, Hi Ca		2.47								
	CaSi	3.18	2.18								
	CaMnSi	3.18	2.18					.73			
Series C	85% FeSi,Std.	3.30	2.47	.090	.049	.07	.08	.69	.04	.11	
	Graphidox		2.44								Ti .085
	SMZ	3.32	2.42					0.81			Zr .01
	Mex. Graphite	3.30	2.15								
	Flake Graphite	3.40									
	85% FeSi,Std.	3.36	2.17								
	50% FeSi,Std.	3.40	2.26								
Series D	Uninoculated	3.28	2.19	.102	.065	N.D.	.07	0.69	0.08	0.18	
	50% FeSi,Std.		2.45								
	75% FeSi,Std.	3.26	2.50								
	85% FeSi,Std.		2.46								
	90% FeSi,Std.		2.54								
	Si Metal	3.46	2.49								
	85% FeSi,Hi Ca	3.28	2.45								
Series E	Uninoculated	3.35	2.27	.089	.058	.03	.06	0.81	0.03	0.11	
	85% FeSi,Hi Ca	3.30	2.55								
	85% FeSi,Hi Ca/ Mex. Graphite		2.38								
	SMZ		2.47					0.88			Zr .08
	Graphidox	3.30	2.37								Ti .04
	CaSi		2.34					0.88			
	CaMnSi	3.29	2.34								

TABLE II - Effect of Inoculation on Transverse and Tensile Properties

		Transverse Properties			Tensile Properties			
	Inoculant	MR/psi	E psi	Defl in.	U.T.S. psi	Y.S. psi .2% offset	E psi	YS/UTS
Series A	Uninoculated	64,630	14.53 x 10^6	.265	36.1 x 10^3	31.5 x 10^3	11.5 x 10^6	.873
	50% Std. FeSi	56,960	12.34	.341	28.5	23.5	9.7	.824
	75% Std. FeSi	56,820	12.54	.302	27.25	24.0	12.1	.880
	85% Std. FeSi	56,040	13.12	.326	29.2	24.6	9.0	.843
	90% Std. FeSi	55,050	13.78	.314	28.65	24.8	9.6	.864
	Si Metal	54,600	12.83	.298	27.4	22.8	9.8	.832
Series B	Uninoculated	67,980	15.92	.283	35.8	30.8	10.9	.860
	85% Std. FeSi	79,060	15.34	.384	40.1	32.4	16.7	.809
	85% FeSi, LoAl	73,500	16.55	.347	38.9	33.6	16.2	.814
	85% FeSi, Hi Ca	80,060	15.54	.383	41.5	-	17.4	-
	85% FeSi, Lo Al,Hi Ca	73,970	16.60	.340	38.7	31.8	15.7	.822
	CaSi	77,780	15.96	.355	41.7	35.8	18.1	.859
	CaMnSi	30,290	15.87	.387	39.6	33.4	11.0	.843
Series C	85% Std. FeSi	60,880	13.69	.315	34.15	28.7	11.3	.841
	Graphidox	62,920	13.35	.320	36.6	29.5	13.5	.806
	SMZ	60,220	13.54	.333	32.6	26.4	14.9	.810
	Mex. Graphite	63,800	13.53	.348	34.6	31.6	14.6	.913
	Flake Graphite	61,220	13.01	.325	33.5	29.6	13.3	.883
	85% Std. FeSi / Flake Graphite	61,200	12.30	.351	32.25	24.9	11.5	.772
	50% FeSi	60,970	14.30	.315	33.2	29.1	15.2	.878
Series D	Uninoculated	65,230	14.40	.340	33.15	27.8	11.5	.838
	50% Std. FeSi	64,240	13.64	.375	32.85	-	15.3	-
	75% Std. FeSi	64,800	13.13	.358	32.9	25.8	13.9	.784
	85% Std. FeSi	64,200	13.88	.379	32.45	28.1	13.0	.866
	90% Std. FeSi	61,450	14.13	.359	30.7	28.0	15.1	.913
	Si Metal	60,000	13.50	.325	31.05	28.3	14.2	.880
	85% FeSi, Hi Ca	65,440	14.46	.385	33.35	26.2	16.5	.786
Series E	Uninoculated	58,120	13.91	.341	29.4	-	15.1	-
	85% FeSi Hi Ca	57,080	11.90	.374	29.1	24.8	16.1	.852
	85% Hi CaFeSi/Mex Graph	58,590	12.20	.374	28.95	25.9	10.8	.895
	SMZ	57,880	13.03	.402	27.7	-	12.0	-
	Graphidox	62,970	13.54	.375	31.8	27.3	15.9	.858
	CaSi	66,330	12.87	.430	31.95	26.6	16.1	.833
	CaMnSi	65,040	13.82	.398	32.6	25.8	13.3	.791

TABLE III - Graphite Flake Size and Type Found in Transverse Bar Section

Percent of Graphite in Various Forms

	Inoculants	A 2 - 3		A 4 - 5	D 4 - 5	D 7 - 8	Other	Traces	Remarks
Series A	Uninoculated			2	81	10	7		B-2,3 Flakes, fine
	50% FeSi,Std.		20	78		2		B-3	extremely fine
	75% FeSi,Std.		14	84		2			blunt
	85% FeSi,Std.		5	95					
	90% FeSi,Std.			70			30		B-4,3 separated by D-8
	Si Metal			90			10		B-4 more "B" at low mag.
Series B	Uninoculated			95		5			fine flakes
	85% FeSi,Std.			98		2			fine
	85% FeSi,Low Al			99+				D-7	
	85% FeSi,Hi Ca			99+				D-7	fine
	85% FeSi,Hi Ca Low Al			96		4			
	CaSi			96		4			coarse
	CaMnSi			98		2			fine
Series C	85% FeSi,Std.			98		2		B	some large Carbon pits
	Graphidox			100					extremely fine
	SMZ			100					thick,coarse
	Mex. Graphite		17	80		3			fine
	Flake Graphite	1		94		5			very fine with some pits
	85% FeSi,Std. Flake Graphite			96		4			
	50% FeSi,Std.			97		3			
Series D	Uninoculated			91		9			
	50% FeSi,Std.	3	30	63		4			very fine
	75% FeSi,Std.	3		88		9			coarse
	85% FeSi,Std.		11	89					
	90% FeSi,Std.	10	14	72		4			
	Si Metal	2	19	76		3			
	85% FeSi,Hi Ca	5	35	60					
Series E	Uninoculated	6	23	56		15			
	85% FeSi,Hi Ca	1	90	8		1			
	85% FeSi,HiCa/ Mex. Graphite		79	20		1			
	SMZ		53	47				D-8	
	Graphidox		87	13				D-8	
	CaSi	2	51	45		2			
	CaMnSi		38	62				D-6	

FIGURE 1: Step Casting for determining effect of Section Thickness on Properties of Cast Iron.

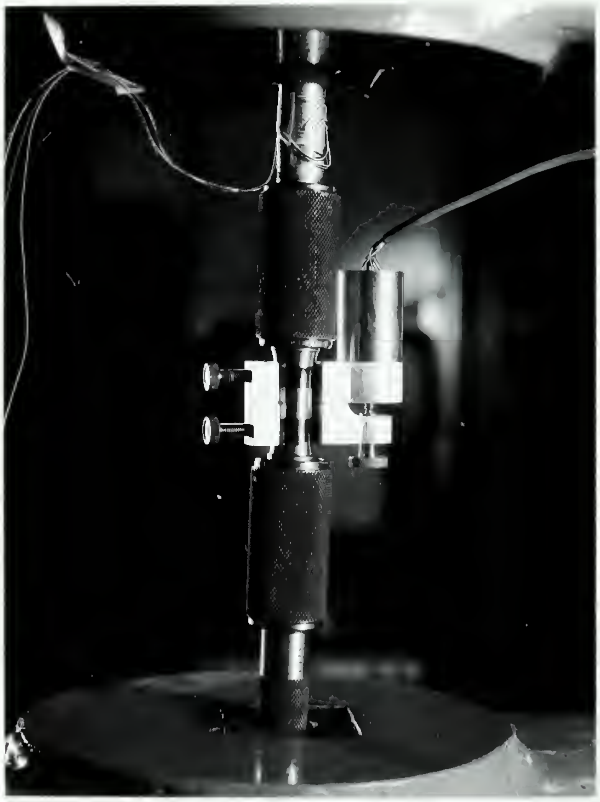


FIGURE 2: Extensometer and Strain Gages for Tension Test of Cast Iron.

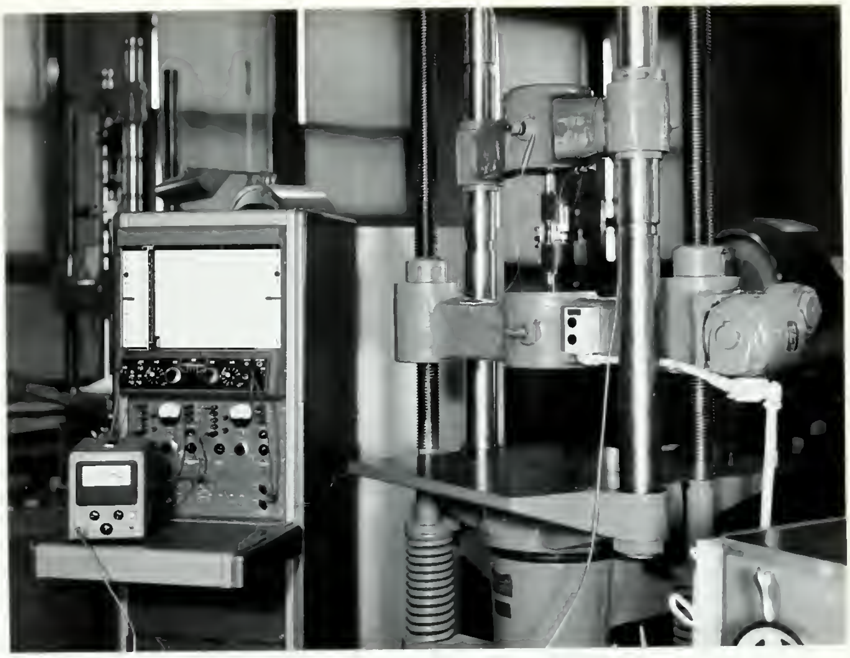


FIGURE 3: Arrangement of Apparatus for Obtaining and Recording Tension Test Data.

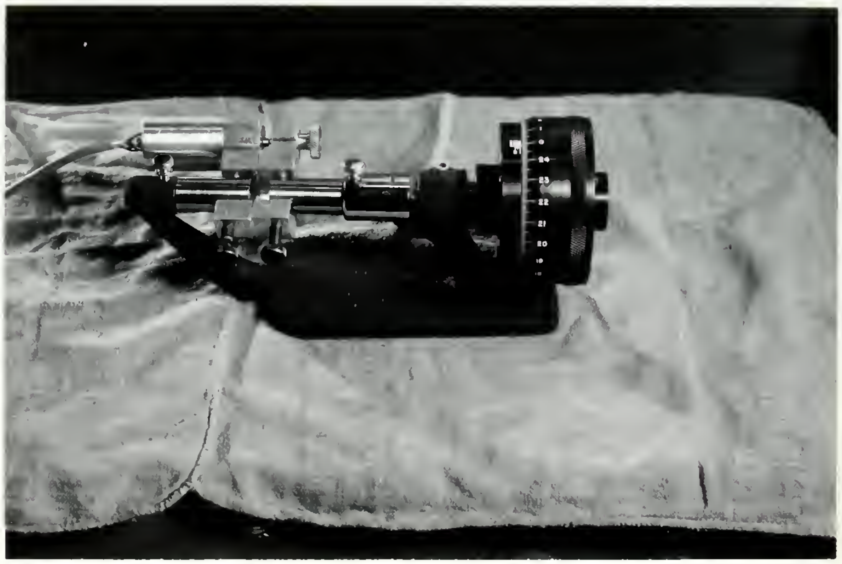


FIGURE 4: Drum Micrometer as Used for Calibration of Extensometer.

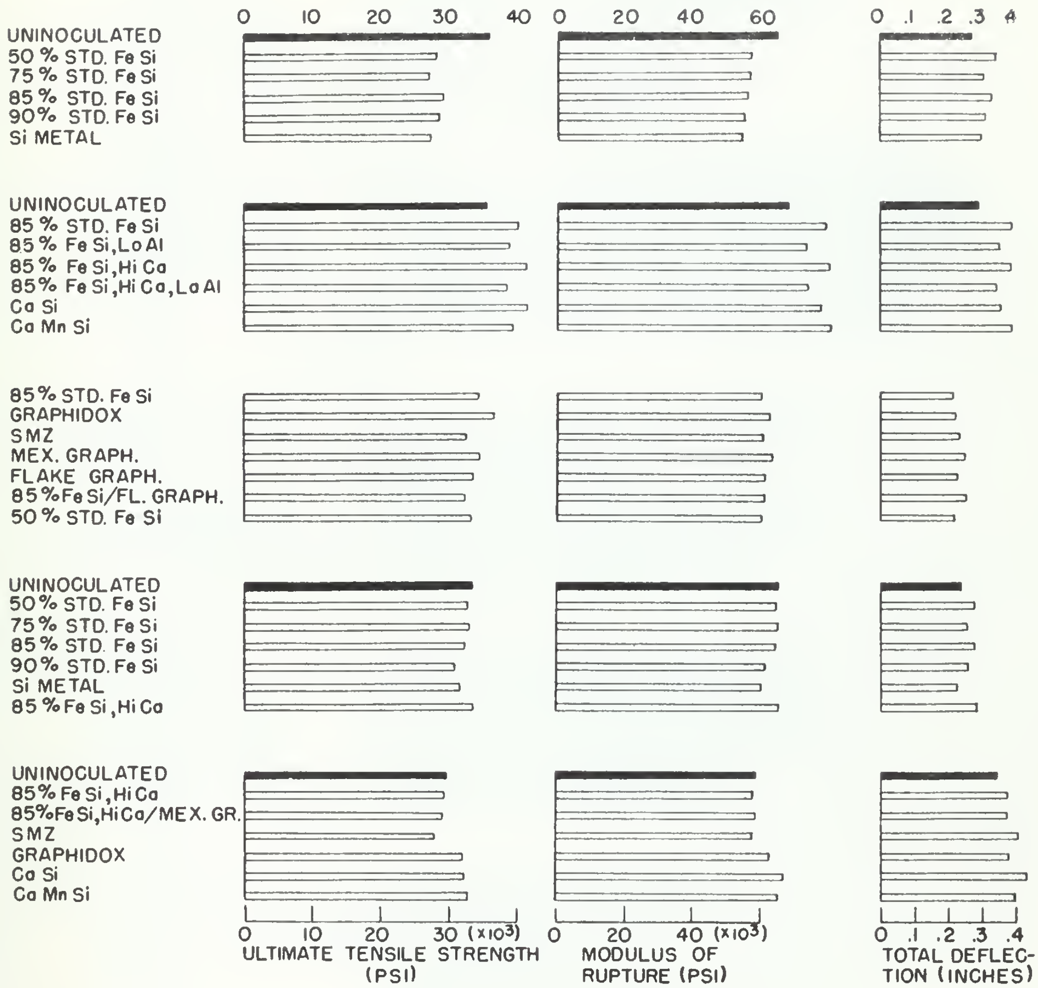
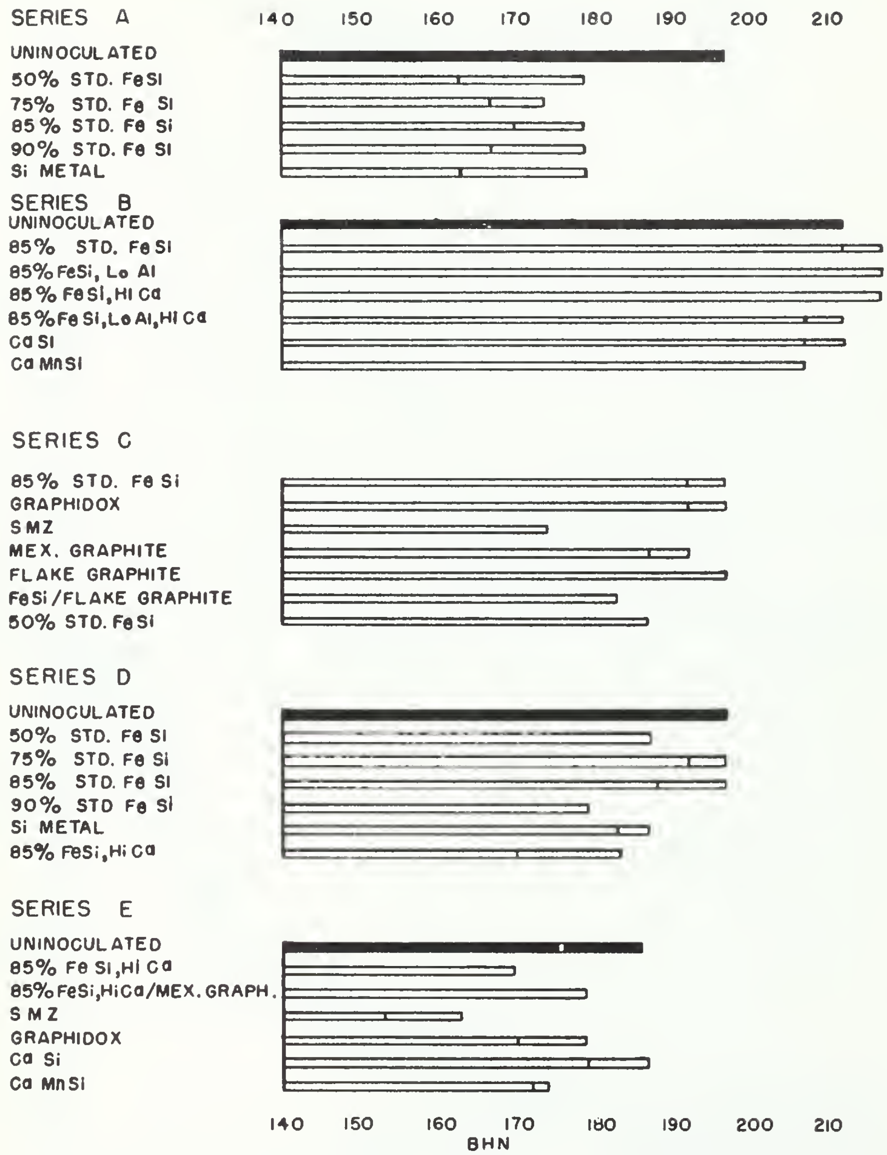
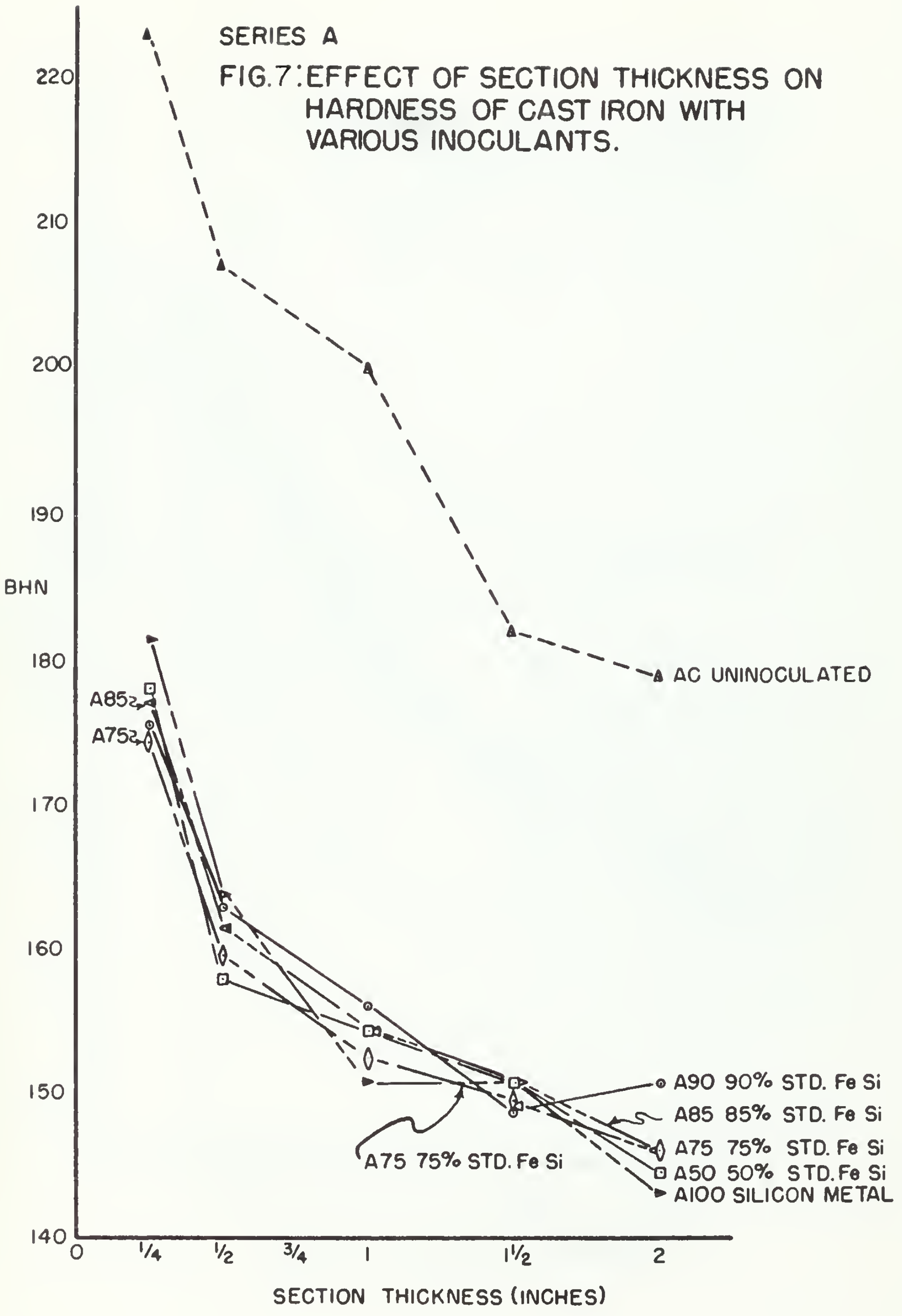


FIG. 5: EFFECT OF VARIOUS INOCULANTS ON TENSILE AND TRANSVERSE PROPERTIES IN EACH SERIES.



NOTE SHORTER LINE IS HARDNESS IN CENTER. FULL LENGTH LINE IS HARDNESS NEAR SURFACE.

FIG.6: EFFECT OF VARIOUS INOCULANTS ON HARDNESS OF TRANSVERSE TEST BARS.


SERIES A
FIG.7: EFFECT OF SECTION THICKNESS ON HARDNESS OF CAST IRON WITH VARIOUS INOCULANTS.
220
210
200
190
BHN
180
170
160
150
140
0
1/4
1/2
3/4
1
1 1/2
2
SECTION THICKNESS (INCHES)
AC UNINOCULATED
A85₂
A75₂
A90 90% STD. Fe Si
A85 85% STD. Fe Si
A75 75% STD. Fe Si
A50 50% STD. Fe Si
A100 SILICON METAL
A75 75% STD. Fe Si

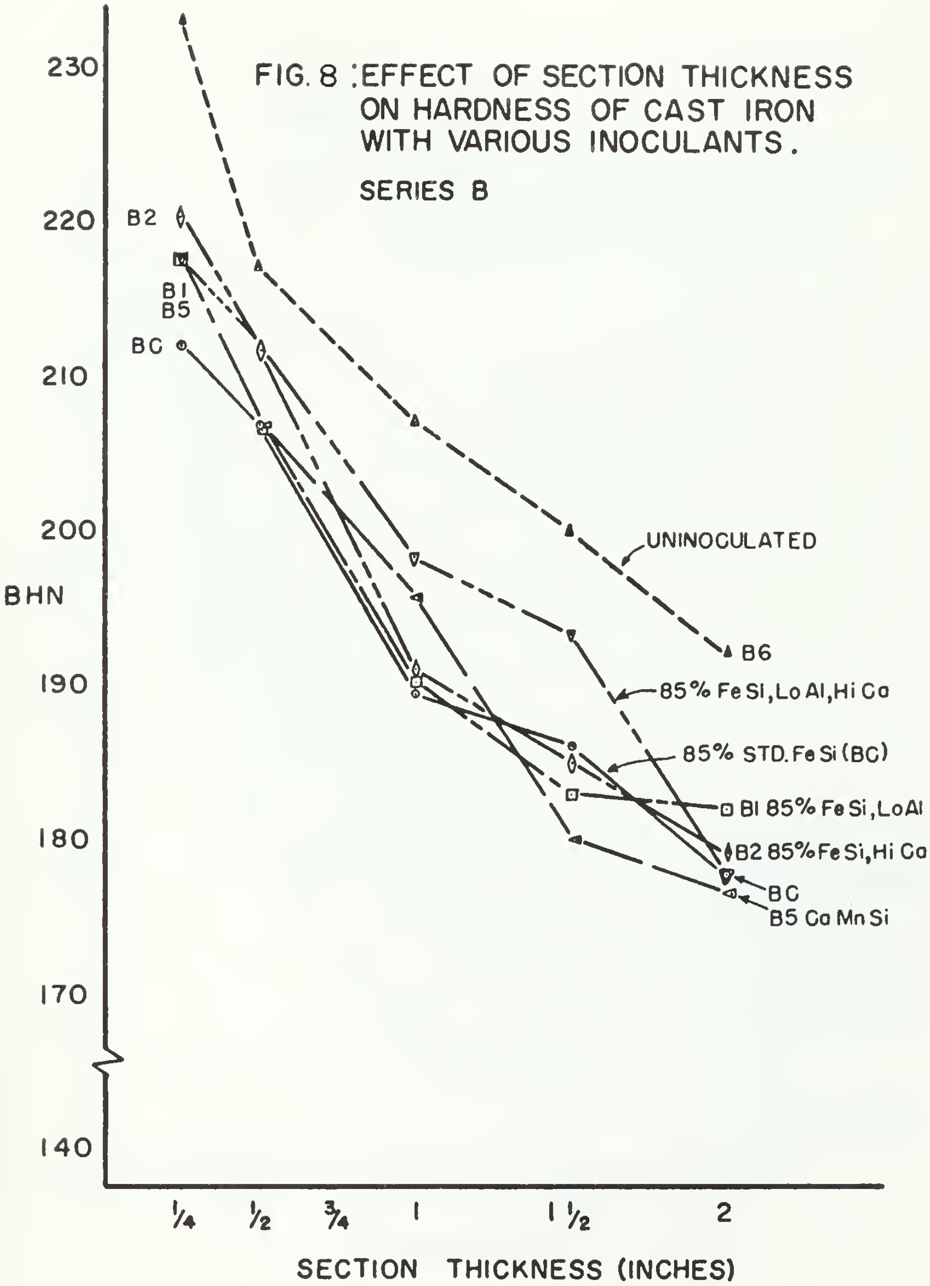
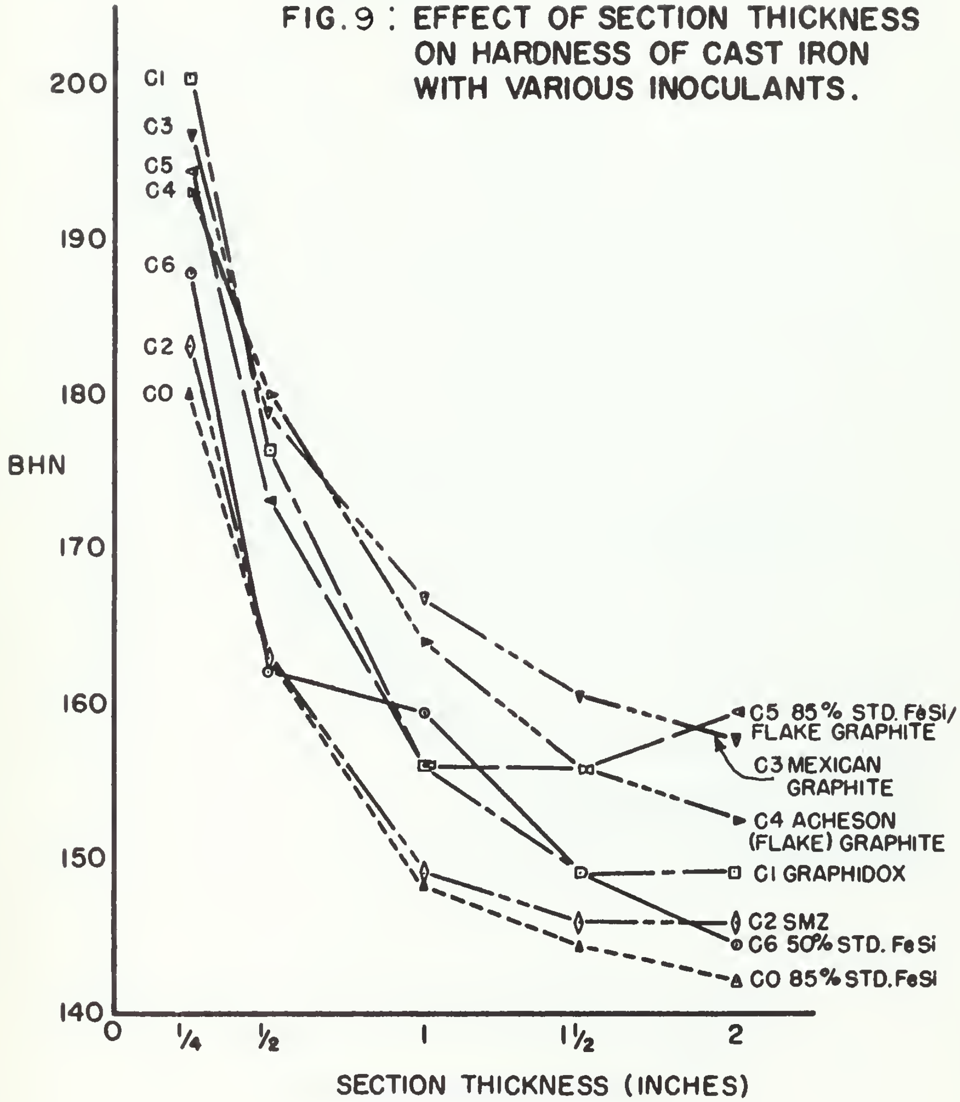


FIG. 8 : EFFECT OF SECTION THICKNESS ON HARDNESS OF CAST IRON WITH VARIOUS INOCULANTS.

SERIES B

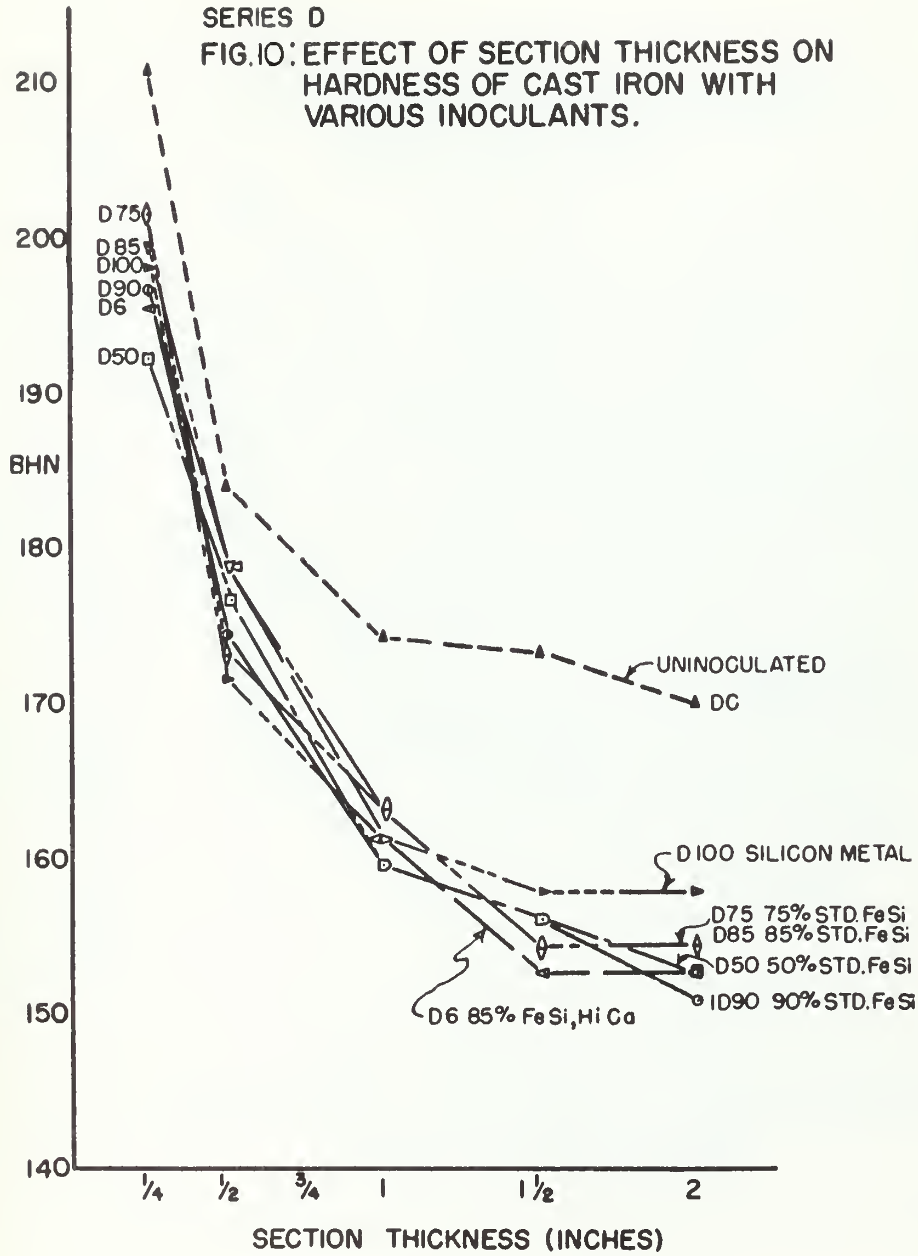
SERIES C

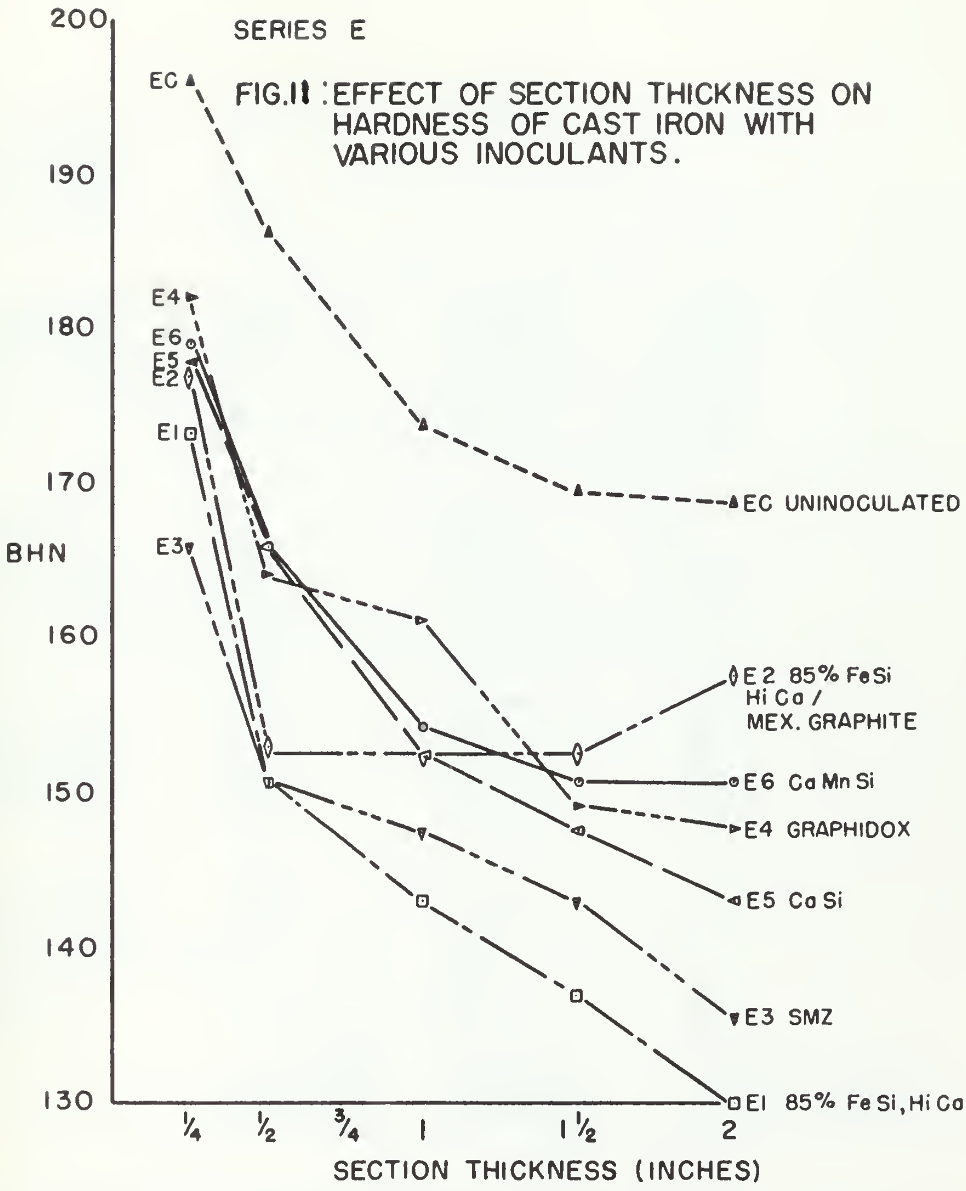
FIG. 9 : EFFECT OF SECTION THICKNESS ON HARDNESS OF CAST IRON WITH VARIOUS INOCULANTS.



SERIES D

FIG. 10: EFFECT OF SECTION THICKNESS ON HARDNESS OF CAST IRON WITH VARIOUS INOCULANTS.




200
190
180
170
160
150
140
130
BHN
SERIES E
FIG.11 :EFFECT OF SECTION THICKNESS ON HARDNESS OF CAST IRON WITH VARIOUS INOCULANTS.
EC
E4
E6
E5
E2
E1
E3
EC UNINOCULATED
E2 85% FeSi Hi Ca / MEX. GRAPHITE
E6 Ca Mn Si
E4 GRAPHIDOX
E5 Ca Si
E3 SMZ
E1 85% Fe Si, Hi Ca
1/4
1/2
3/4
1
1 1/2
2
SECTION THICKNESS (INCHES)

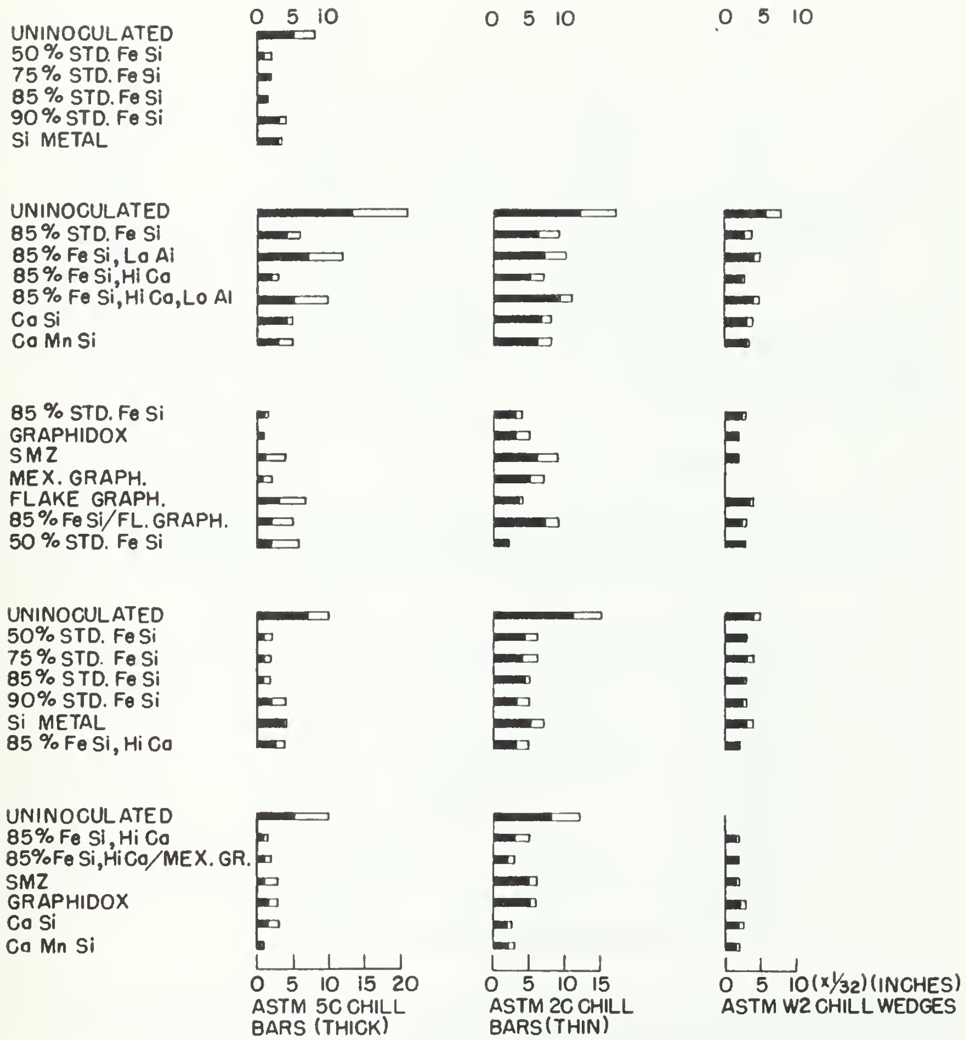
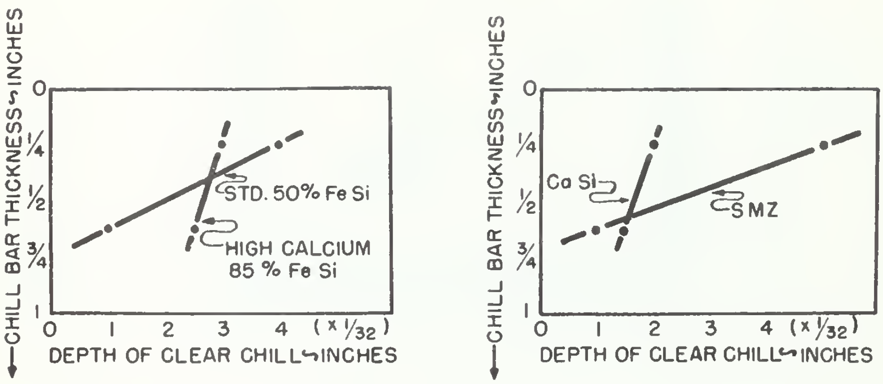


FIG. 12: EFFECT OF VARIOUS INOCULANTS ON TOTAL CHILL AND CLEAR CHILL IN EACH SERIES.



A. SERIES D

B. SERIES E

FIG.13: EFFECT OF CHILL BAR THICKNESS ON DEPTH OF CLEAR CHILL FOR VARIOUS INOCULANTS.

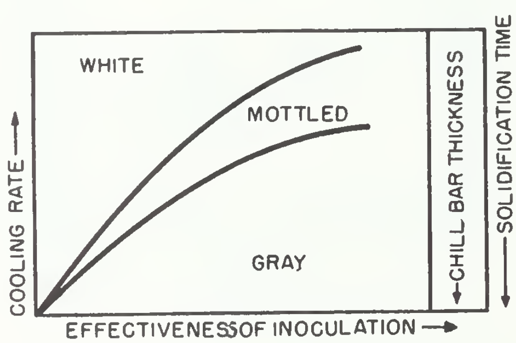


FIG. 14: EFFECT OF COOLING RATE AND RATE OF INOCULATION ON MODE OF CAST IRON SOLIDIFICATION.

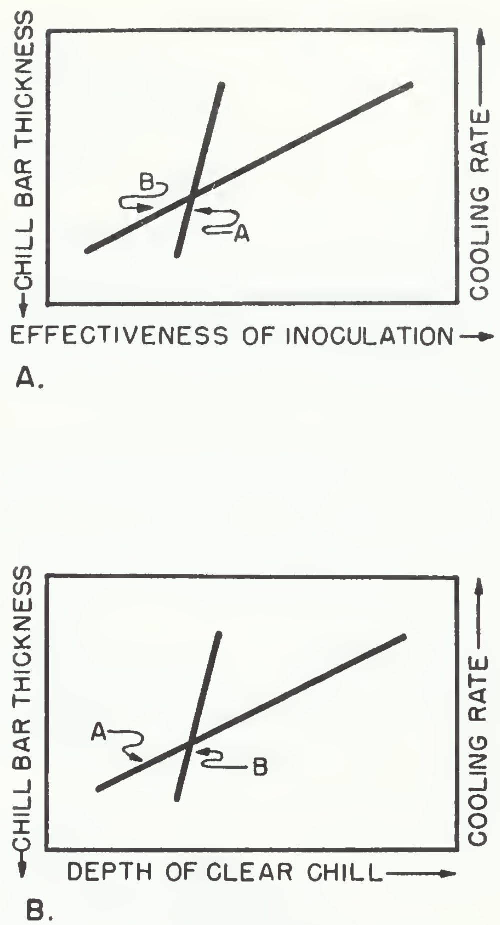


FIG. 15: SCHEMATIC REPRESENTATION OF RELATION BETWEEN COOLING RATE AND INOCULATION EFFECTIVENESS ON DEPTH OF CHILL.

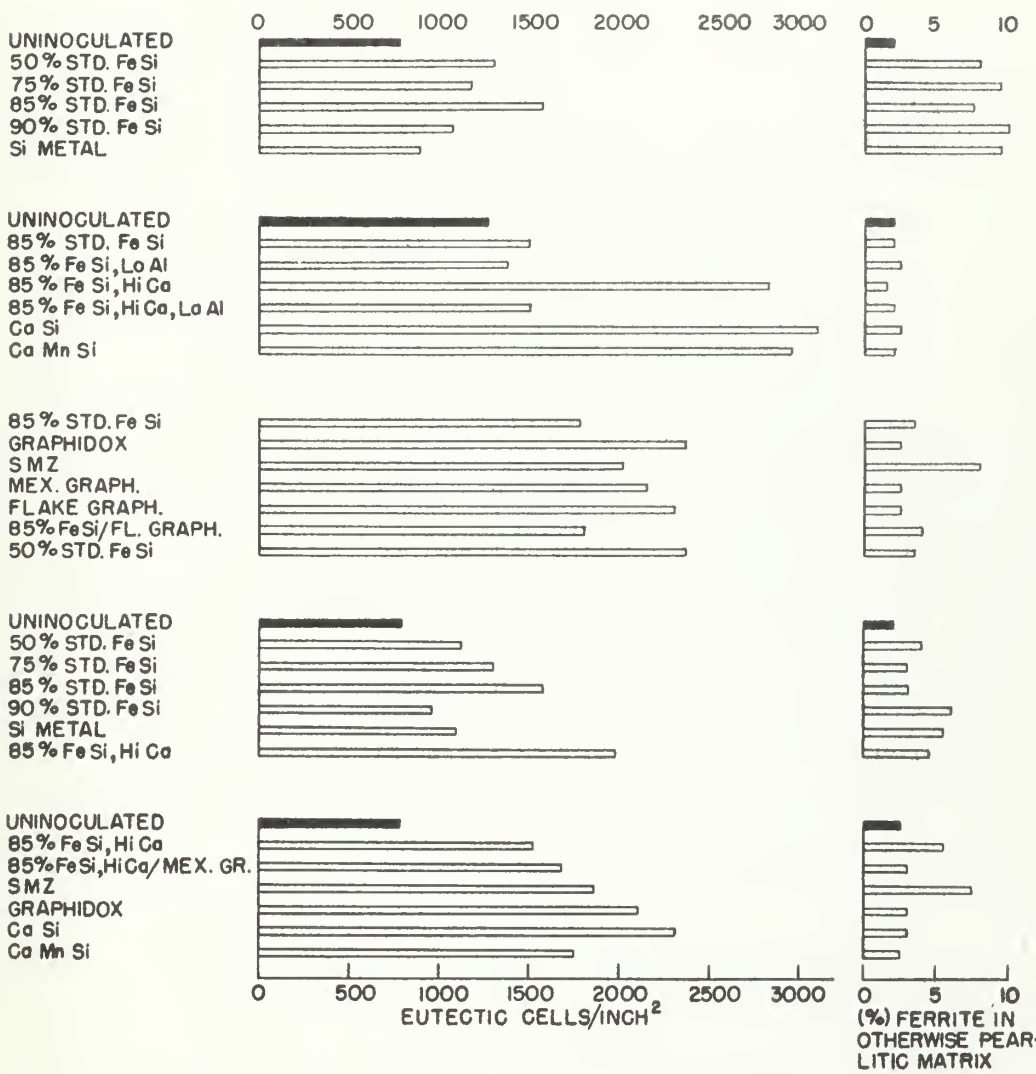


FIG. 16: EFFECT OF VARIOUS INOCULANTS ON MICROSTRUCTURE IN EACH SERIES.